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Experimental and theoretical study of frost melting water retention on fin surfaces with different surface characteristics

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ABSTRACT

There is some frost melting water retention on the surface of fin-tube heat exchanger during defrosting process. It takes much time and energy to evaporate the retained water. In this paper, the effect of fin surface characteristic on frost melting water retention is investigated experimentally. Visualization experiment shows that fin surface characteristic has a significant influence on water retention. The retained water forms a thin water film on the hydrophilic fin, while only a few small spherical droplets stay on the superhydrophobic fin. The retained water mass of the superhydrophobic fin decreases by 79.82%, 75.82% and 66.15% compared with that of the hydrophilic, bare and hydrophobic fins, respectively. The frosting time over 30 min has a subtle effect on retained water mass of the hydrophobic and superhydrophobic fins. A mathematical model, which considers the surface contact angle and contact angle hysteresis, is further developed to predict the maximum retained droplet radius and retained water mass. The model is verified to be accurate when the contact angle lied in the range of 110–150°.

1. Introduction

With the development of surface treatment technology in recent years, various surface-treated materials have been widely applied to various domains, such as anti-frosting for fin surfaces in air source heat pumps. It is well-known that the phenomenon of frost formation on fin surfaces of the outdoor heat exchanger is unavoidable when an air source heat pump is used for heating in winter. Frost layer adversely affects the performance of the heating unit due to the increase of the heat transfer resistance and air pressure drop, and even result in the mechanical failure of the heating unit [1,2]. Therefore, the effective anti-frosting method is significant to improve the heating efficiency of air source heat pump.

There have been some researches on the effect of surface characteristic on droplet condensation and frost growth. Dietz et al. [3] investigated the droplet departure frequency with the help of environmental scanning electron microscopy and its implications to enhancing the rate of dropwise condensation on superhydrophobic surfaces. Rykaczewski [4] and Enright et al. [5] carried out experiments to study the droplet condensation mechanisms on superhydrophobic surfaces. Enright et al. [5] also elucidated how local energy barriers were essential to understand non-equilibrium condensed droplet morphologies and how the wetting states were affected by the nucleation density of the droplets. Huang et al. [6] experimentally investigated the effect of contact angle on water droplet freezing and the experimental results showed that the contact angle has a strong influence on water droplet freezing time. Okoroafor and Newborough [7] tested the restrained frost ability of a hydrophilic surface in over two hours and the results indicated that the reduction in the frost growth rate and frost thickness lied in the range of 10%–30%. Wang et al. [8] prepared a hydrophobic surface whose contact angle was 147° and the frost on the surface was delayed for 60 min compared with that of a neat surface. Liu et al. [9] and Cai et al. [10] studied and compared the growth characteristics of the frost layer on different surfaces, such as the frost thickness, frost mass and frost morphology.

There have been a few researches on the effect of surface characteristic on defrosting process. Kim et al. [11] investigated the characteristics of frosting and defrosting on a fin according to its surface contact angle and results showed that the effect of surface treatment on defrosting time was insignificant. Jhee et al. [12] reported the effects of the surface characteristics on frosting/defrosting behavior in a fin-tube heat exchanger and revealed that the amount of retained water on the surface-treated heat exchangers was smaller than that of the bare heat exchanger. Rahman et al. [13–15] studied the drainage of frost melting water from a number

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Nomenclature

F_c	adhesive force (N)
r	radius of retained droplet (mm)
θ	contact angle (°)
θ_r	receding contact angle (°)
θ_a	advancing contact angle (°)
V	volume of retained droplet (m^3)
F_g	gravity of retained droplet (N)
N_s	nucleation site density ($1/cm^2$)
m	retained water mass (kg)
Greek symbols	
σ	surface tension (N/m)
ρ	density of retained droplet (kg/m^3)

of microgrooved brass surfaces in multiple frost/defrost/refrost cycles, and their experiments showed that microgrooved surfaces drained up to 70% more condensate than the flat baseline did. There is some water retention on fin surfaces after frost melting because of the adhesive force. It takes much more time and energy to evaporate the retained water compared with those of frost melting. If the retained water is not evaporated completely, it will freeze again and form a dense frost layer in the next frost period. In a word, the retained water has an adverse influence on both frosting and defrosting processes. Therefore, an in-depth understanding of frost melting water retention on fin surfaces is significant to reduce the retained water and improve the defrosting efficiency.

In this paper, a series of fin samples with different surface characteristics were prepared and the effect of surface characteristic on frost melting water retention was investigated experimentally. A mathematical model, which considered the surface characteristics including the contact angle and contact angle hysteresis, was further developed to predict the maximum retained droplet radius and retained water mass.

2. Experiments

2.1. Experimental platform and procedure

Fig. 1 is the schematic diagram of the experimental platform [16]. A cold platform was used to implement the frosting process and defrosting process of the fin. The semiconductor thermoelectric refrigeration was applied for the cold platform. The surface temperature of the cold platform was regulated from −20 to 150 °C by using a temperature controller. The cold platform was placed vertically in the experiment and the fin was fixed on it. An image acquisition system, which includes a CCD video camera, an asana microscope and image acquisition cards, was used to observe and record the behaviors of the frost melting water retention. The side and front photographs of the water retention were recorded by the CCD video camera and asana microscope, respectively, and then were transmitted to a computer.

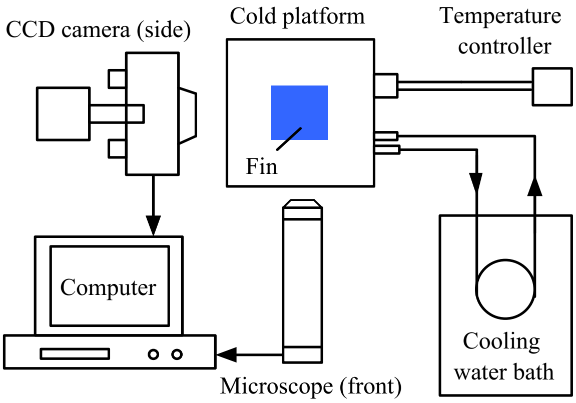

Fig. 1. Schematic diagram of experimental platform.

In the experiment, four types of fins with different surface characteristics were prepared, and the contact angle θ and contact angle hysteresis $\triangle\theta$ were measured, as shown in Fig. 2. The measurement of the contact angle was performed using OCA 15 Pro apparatus by the pendant drop method, and the volume of the water droplet was 4 μL. The measurement of the contact angle hysteresis was performed by the tilting plate method. A water droplet with volume of 10 μL was dropped on the sample platform of the OCA 15 Pro apparatus, and then the sample platform was continuous tilted. When the water droplet just rolled, the tilt angle of the sample platform was the contact angel hysteresis.

The hydrophilic and bare fins were directly obtained from fin-tube heat exchangers of air source heat pumps. The hydrophobic and superhydrophobic fins were prepared by using the sodium hydroxide solution etching method. The size of the fins is 4 cm × 4 cm. Before the experiment, the fin was fixed on the platform vertically. The surface temperature of the cold platform was set to −10 °C for frosting. After frosting, the platform temperature was raised to 50 °C (at a temperature rise rate of 8 °C/s) for defrosting. When there was no melting water flowing from the fin surface, the retained water mass was measured. The experimental conditions were the air temperature of 4.5 °C and air relative humidity of 65%.

2.2. Parameters measurement

The most important parameters were the retained droplet radius r and retained water mass m. The retained droplet radius was measured by a comparative method. In Fig. 3(a), the length of each grid in the scale plate is 0.1 mm. The photographs of the droplets were compared with the scale plate under the same magnification. As shown in Fig. 3(b), the measured value d_c was calculated through the number of the grids occupied by the droplet, and the r was calculated according to the relationship between r and d_c.

An electronic balance, with accuracy of 0.001 g and measuring range of 0–220 g, was used to weight the retained water. After frost melting, a piece of absorbent paper, which attracts water very well, was used to absorbed the retained water quickly and thoroughly, and then the retained water was weighed together with the absorbent paper. In order to verify the accuracy of the measurement process of retained water mass, an independent experiment was carried out. Firstly, the mass of a fin was weighted by the electronic balance and some water was dropped on the fin surface. Then the fin with the water on its surface was weighted together. The difference value between the two weighted values was the actual water mass on the fin surface. Next, a piece of the absorbent paper was used to absorbed the retained water quickly and thoroughly and then the retained water was weighed together with the absorbent paper. Compared the value measured by the method above with the actual retained water mass, the measuring error is shown in Fig. 4. The measuring error was less than 3% in 7 times repeated